BOOST-BASED MPPT CONVERTER TOPOLOGY TRADE-OFF FOR SPACE APPLICATIONS

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Introduction

High power and high voltage – 100V – power buses are often required not only in the frame of the telecommunication spacecrafts, but also for those scientific and interplanetary mission cases where a high user power load demand is driving the design of the power subsystem. On many cases, the use of Maximum Power Point Tracking (MPPT) is essential for an optimum power subsystem sizing.

The adaptation to 100V of the existing MPPT concepts for 28V buses – like GOCE, ROSETTA, etc. – is not immediate, as happens in general terms with the upgrading of Power Conditioning Units from 28V to 50V and 100V. Moreover, for those cases where the solar array voltage is under the bus voltage, a step-up boost power cell is mandatory for the MPPT implementation.

This paper will focus on the definition of the main performance characteristics that must have a converter power cell to fit the above mentioned application range. Starting with the establishment of the relevant trade-off parameters, in terms of power handling capability, input and output operational voltage ranges (both in nominal and emergency conditions), conducted emissions, bus capacitor and solar array output impedance considerations, several candidate topologies are analysed: conventional boost, interleaved DCM and CCM boost, two inductor boost, boost with ripple cancellation and boost with switch near ground. Some critical aspects like mass, efficiency and number of reactive and power switching elements are also covered.

Special attention is paid to the feasibility of the design for the control loop that will govern the converter operation when forming part of a PCU, taking into account the effects of the RHPZ inherent to most of the boost converter topologies. Some of the candidate topologies where prototyped to demonstrate in the laboratory the performances identified during the analysis phase.

Power Topologies Review

Five boost derived power topologies will be reviewed in this paper. In the following paragraphs these topologies are presented.

Classical boost converter

This very well known topology is shown in figure 1. Its simplicity is its main advantage. If it is designed in continuous conduction mode (CCM), it may suffer high power losses due to the reverse recovery of the diode. Moreover in CCM, the presence of the right half plane zero (RHP zero) may cause a limited bandwidth. Discontinuous Conduction mode (DCM) avoids these two problems but it increases the rms currents across the power components.

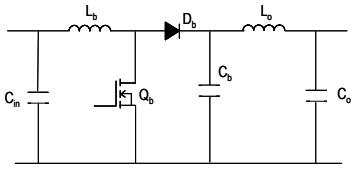

Figure 1.- Classical boost converter

Interleaved boost converter

Two half-power identical power stages can be paralleled to build a the converter (see figure 2). By shifting 180º the driving signal of the transistors, the filters are drastically reduced.

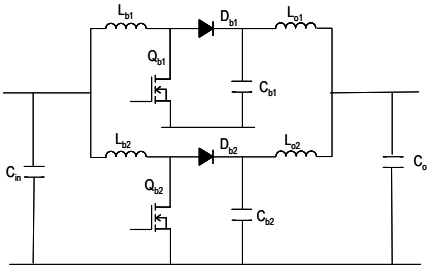

Figure 2.- Interleaved boost converter

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The comments about CCM and DCM made for the classical boost converter are valid for this variation. However, in CCM, it is necessary to include the equalization of the currents (this is not a problem in current mode control but it requires two current sensors).

Two inductor boost converter

The main advantage of this two inductor boost converter (figure 3) is that both input and output current are continuous [1]. However, there are two power inductors. The current ripple in each inductor is exactly the same than the classical boost since the voltage applied to them is V_{IN} during on time and V_{IN}-V_O during off-time.

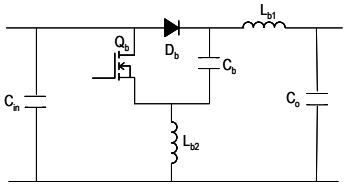

Figure 3.- Two inductor boost converter

Boost converter with ripple cancellation

This topology is derived from the two inductor boost converter [2]. An additional branch has been included to cancel the input current (see figure 4). Basically, the converter operates as a two inductor boost converter with some additional components. The cancellation branch is composed by L2, Cbb and coupled winding Lb1_c. Cbb is a blocking capacitor that holds a voltage equal to the input voltage. The coupled inductor polarises inductance L2 in such a way that the addition of its current ripple (it has no dc current) is the opposite that the current demanded by the converter. Thus, the addition of both is almost zero at every input voltage.

L3 is filtering the output current and, therefore, most of the magnetising current of inductor Lb flows through b1_b winding.

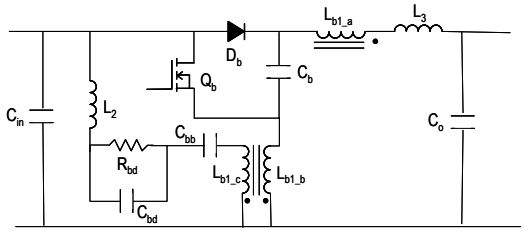

Figure 4.- Boost converter with ripple cancellation

Boost with switch near ground

The last topology of this analysis was presented in [3]. Previous works [4] shows this topology without LC filter. An additional coupled winding allows advantages regarding the RHP zero of the boost converter. Moreover, compared with some of the previous topologies, the power transistor is grounded making easy the implementation of the driving circuit.

The main advantage of this circuit is that thanks to the additional winding Lb_b, there is direct energy transfer between input and output during transistor on-time. This allows, in certain conditions [5], to remove the RHP zero of the boost converter. The turns ratio of the coupled inductor Lb plays an important role in the converter. With it, the converter behaviour runs from a conventional boost to a low ripple boost.

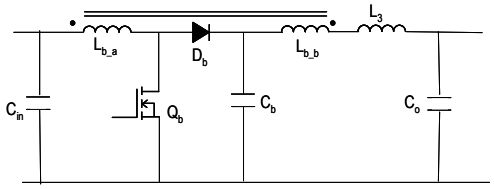

Figure 5.- Boost converter with switch near ground

In particular, in the next analysis, we will try to determine the following features:

- **Weight**: one of the priorities is to reduce the weight of the converter. The weight will be determined mainly by the inductors (core and windings) and capacitors.
- **Bandwidth**: In certain conditions, high negative current steps will be applied to the converter. Thus, a high bandwidth together with small energy-storage converter is desirable. Bode plots will be obtained to foresee the potential capabilities from the point of view of the control.
- **Efficiency**: should be as high as possible but keeping in mind that 97% is required. The power losses will be evaluated in the inductors and MOSFET.

Design for Static Conditions

Specifications

Each power converter is designed for 500W. Solar array provides a voltage between 40 and 96V being the battery voltage equal to 100V in nominal conditions. Since all these boost circuits have the same dc gain, there are no differences in the duty cycle range.

To compare the topologies, the switching frequency has been fixed to 130kHz. In order to make a proper comparison, all the designs should comply the following conditions:

- **Input current ripple**: limited to 20% peak to peak of the nominal current in the worst case line condition.
- **Output voltage ripple**: limited to 0.5% of the nominal output voltage.
- **Output capacitor:** the minimum output capacitance (for impedance reasons) has been fixed around 41 μF (normalized value of 47 μF).

- **Voltage ripple of floating capacitors:** in several topologies, there are one or two flying capacitors. They have been designed to obtain a 5% voltage ripple. In some cases, the capacitor has been increased to meet the rms currents imposed by the circuit.

The parts used in the design of these circuits are:

- **Inductors**: they should be designed using Magnetics MPP toroidal cores (its density is 8.7 gr/cm^3). The main criteria is size but the inductor should match filling factor (25%), power losses (<1%) and using AWG22 with 5 maximum parallel windings. It will be noted if some of these requirements are not accomplished.
- **Capacitors:** Self Healing PM94 Eurofarad capacitors have been used for this comparison.
- **Transistors:** Power Fet N-channel IRHMS57260SE have been used for this comparison as all switches have the same voltage stress and similar rms current. The interleaved boost topology has a reduced rms current but the other available MOSFETs within the used technology have more power losses.

In the following paragraphs, the main data obtained from the design of these boost topologies are shown. The power losses shown in the tables correspond to 40V input voltage which is the worst-case because conduction losses are predominant. The inductors have been designed for the highest ripple condition that takes place at 50V. The capacitors have been selected according to the capacitance and maximum rms current.

Classical boost converter

CONVENTIONAL BOOST		Value	Weight	Losses
INDUCTORS	L_b	96µH	142,7gr	4,1W
	L_o	2,4µH		
CAPACITORS	C_b	4,7µF	65,1gr	
	C_o	47µF		
MOSFET				11,74W
Total weight			207,8gr	
Total losses				15,84W

Table 1.- Main parameters of the classical boost converter

Interleaved DCM boost converter

Unfortunately, this design does not comply with the restriction of 20% input current ripple. Therefore, it will be considered in CCM. However for smaller currents it seems a very good option.

INTERLEAVED DCM BOOST CONVERTER		Value	Weight	Losses
INDUCTORS	L_{b1}	12,4µH	94,94gr	17W
	L_{b2}	12,4µH		
	L_{o1}	1,2µH		
	L_{o2}	1,2µH		
CAPACITORS	C_{b1}	4,7µF	66,2gr	
	C_{b2}	4,7µF		
	C_o	47µF		
MOSFET				10,44W
Total weight			161,14gr	
Total losses				27,44W

Table 2.- Main parameters of the interleaved DCM boost converter

Interleaved CCM boost converter

The inductances have been selected to meet the 20% input voltage ripple requirement. Current ripple depends on input voltage but also ripple cancellation factor. Therefore, to determine the worst-case input current ripple, it is necessary to account for both. Figure 6 shows this issue. Worst case occurs at 75V.

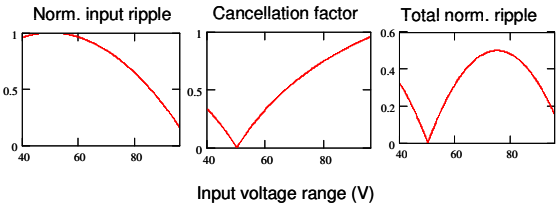

Figure 6.- Current ripple in the interleaved boost converter

Thanks to the partial cancellation of the inductor currents, the inductance can be decreased compared with the other topologies.

INTERLEAVED CCM BOOST CONVERTER		Value	Weight	Losses
INDUCTORS	L_{b1}	43µH	97gr	6,96W
	L_{b2}	43µH		
	L_{o1}	1,2µH		
	L_{o2}	1,2µH		
CAPACITORS	C_{b1}	3,3µF	64gr	
	C_{b2}	3,3µF		
	C_o	47µF		
MOSFET				12,96W
Total weight			161gr	
Total losses				19,92W

Table 3.- Main parameters of the interleaved CCM boost converter

Two inductor boost converter

In this case, to achieve 20% input current ripple, it is necessary to guarantee a 10% in each inductor. The reason is that both inductors have exactly the same current ripple and the addition of both flows through the input. Therefore, the mass is a very big penalty for this topology.

One of the advantages of this converter is the small output current ripple that allows a smaller output capacitor. However, in this design, this advantage is lost because a minimum of 47µF is placed in the output for impedance reasons.

TWO INDUCTOR BOOST		Value	Weight	Losses
INDUCTORS	L_{b1}	192µH	268,3gr	4,7W
	L_{b2}	192µH		
CAPACITORS	C_b	8,2µF	67,8gr	
	C_b	47µF		
MOSFET				11,74W
Total weight			336,1gr	
Total losses				16,44W

Table 4.- Main parameters of the two inductor boost converter

Boost converter with ripple cancellation

From the point of view of the inductors, this converter is quite different. It has three inductors and one of them with three windings. However, since the main inductor current ripple is fully cancelled with the auxiliary branch, the inductance can be reduced obtaining a small value. Then, regarding the inductors, this converter shows one of the minimum mass.

BOOST RIPPLE CANCELLATION		Value	Weight	Losses
INDUCTORS	L_{b1_a}	51µH	91,56gr	2,8W
	L_{b1_b}	51µH		
	L_{b1_c}	2,4µH		
	L_2	7,2µH		
	L_3	3µH		
CAPACITORS	C_{bb}	3,3µF	70gr	
	C_{bd}	3,3µF		
	C_b	4,7µF		
	C_b	47µF		
MOSFET				11,6W
Total weight			161,56gr	
Total losses				14,4W

Table 5.- Main parameters of the boost converter with ripple cancellation

Boost with switch near ground

This converter has an additional degree of freedom that has been selected to decrease the size of the inductors. Thus a turns ratio of 10:1 has been selected. Even with this design, there is no advantage from the point of view of the weight being one of the worst options.

BOOST SWITCH NEAR GROUND		Value	Weight	Losses
INDUCTORS	L_{b1_a}	128µH	223,94gr	5,2W
	L_{b1_b}	1,28µH		
	L_3	3,8µH		
CAPACITORS	C_b	6,8µF	63,7gr	
	C_b	47µF		
MOSFET				11,74W
Total weight			287,64gr	
Total losses				16,94W

Table 6.- Main parameters of the boost converter with switch near ground

Control loop & bandwidth issues

The objective of this section is to evaluate the capabilities of each topology to offer a high bandwidth. To account this, each topology has been modeled and analyzed. The following bode plots have been obtained from the simulator. Those are plotted from 10Hz to 1MHz.

Classical boost converter

The bode plot shows a dynamic response with two poles and a right half-plane zero, a typical boost frequency response. At high frequency, magnitude falls at 20dBs/dec and phase ends at -270º. At very high frequency it can be seen the effect of the output filter.

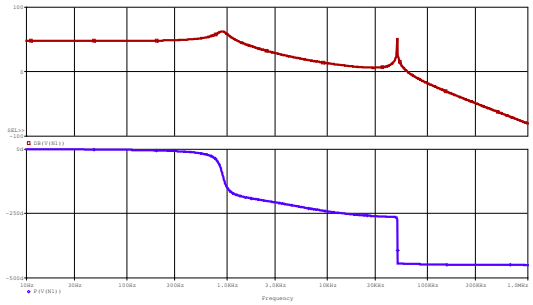

Figure 7.- Bode plot of d to Vs of the conventional boost converter

Interleaved CCM boost converter

The dynamic response of the CCM interleaved boost converter shows a boost converter dynamic response with output LC filter, with small differences in the resonance and the RHP zero frequency. The resonance frequency takes place at higher frfequency allowing a higher bandwidth

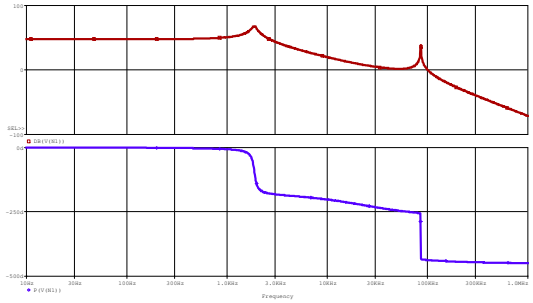

Figure 8.- Bode plot of d to Vs of the interleaved CCM boost converter

Two inductor boost converter

The Bode diagram of figure 9 shows two right half-plane zeroes and four poles.

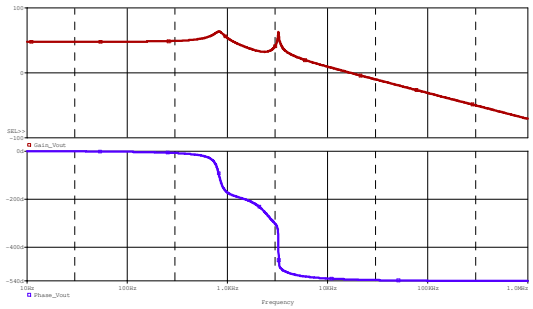

Figure 9.- Bode plot of d to Vs of the two inductor boost converter

Boost converter with ripple cancellation

In low and medium frequencies, the transfer function of d to Vs shows a classical boost equivalent transfer

function. However, at higher frequency there are additional poles and zeroes. These poles and zeroes do not have influence on the control stage design.

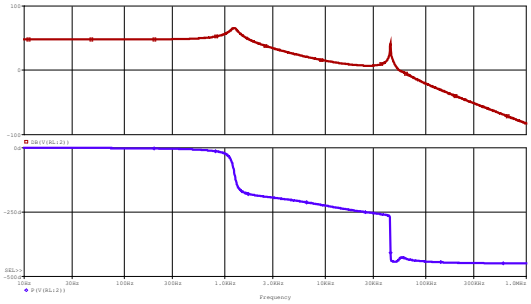

Figure 10.- Bode plot of d to Vs of the boost converter with ripple cancellation

Boost with switch near ground

The Bode diagram (figure 11) shows two right half-plane zeroes and four poles. As it can be seen, the transfer function is more complex at very high frequencies but in general the bandwidth will be similar to the classical converter.

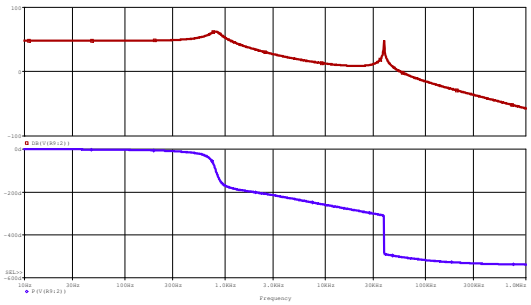

Figure 11.- Bode plot of d to Vs of boost converter with switch near ground

The right half plane zeroes cancellation in this topology depends on the turns ratio. For this particular design, the RHP zeroes are not cancelled.

Summary

The last three topologies exhibit a much more complex transfer function at high frequency. The bandwidth is similar in all of them. Therefore, the conventional boost (interleaved or not) has a small advantage from this point of view. In the comparison section, the bandwidth can be estimated using the resonance frequency obtained in this analysis.

Experimental results

Some of these circuits have been prototyped. In particular, the three less-conventional circuits have been built and tested. In this section some experimental waveforms obtained from the prototypes are included.

Two inductor boost converter

Figure 12 shows the main waveforms of the prototype. As it can be seen both inductors currents have exactly the same current ripple (note the different vertical scale)

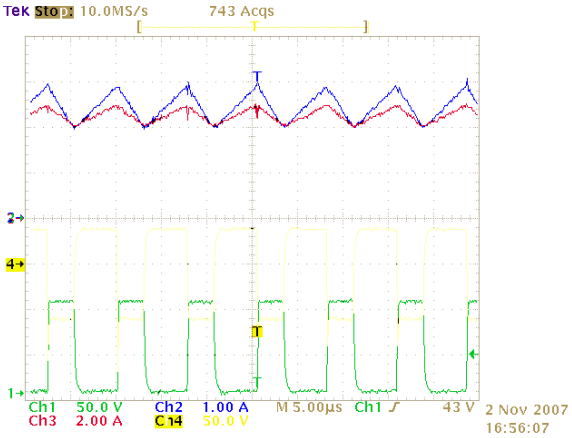

Figure 12.- Main waveforms of the two inductor boost converter: current through the two inductors (1A/div and 2A/div) and the drain to source voltage (50V/div) at 5µs/div

Boost converter with ripple cancellation

In figure 13 can be seen the main waveforms of this converter. It can be seen that the main boost current is cancelled with the cancellation branch.

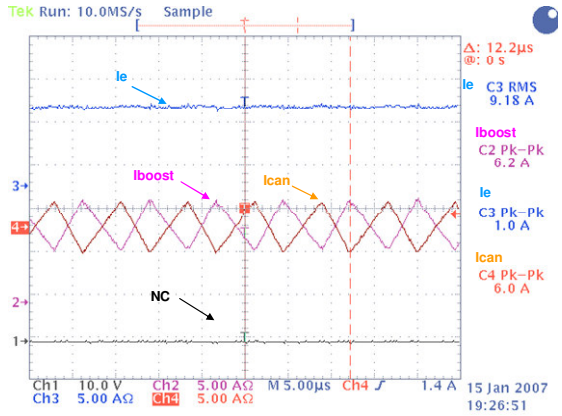

Figure 13.- Main waveforms of the boost converter with ripple cancellation: Input current (5A/div), boost main current (5A/div) and ripple cancellation branch current (5A/div) at 5µs/div.

Figure 14 shows the same waveforms in other conditions, being the converter in DCM. It can be seen that the cancellation characteristic is preserved even when the conduction mode changes.

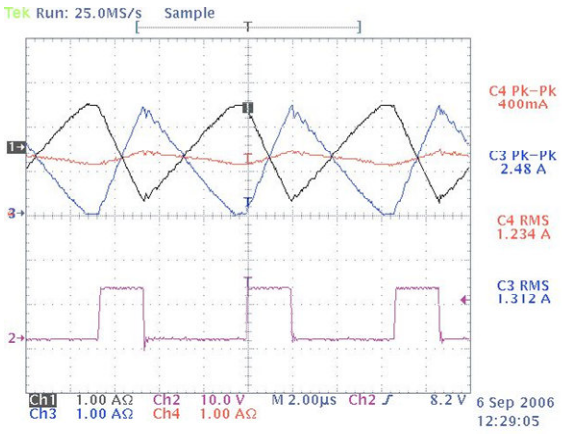

Figure 14.- Main waveforms of the boost converter with ripple cancellation: Input current (1A/div), boost main current (1A/div), ripple cancellation branch current (1A/div) and gate to source voltage (10V/div) at 2µs/div.

Boost with switch near ground

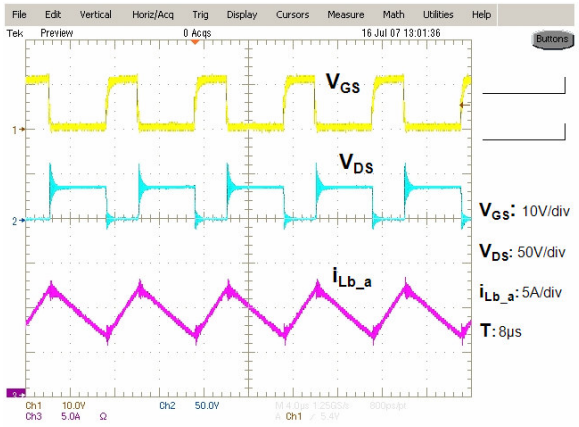

Figure 15.- Main waveforms of the boost converter with switch near ground: gate to source voltage (10V/div), Drain to source voltage (50V/div) and input current (5A/div) at 8µs/div

Figure 15 shows the main waveforms of this converter. This particular prototype was designed to operate in different conditions to check the RHPZ cancellation reported in [6].

Summary and comparison

Table 7 summarises the previous analysis in terms of number of devices, weight, power losses and control.

It is difficult to select one of these topologies as the best because it depends on the specific parameter. From the point of view of weight, topologies 2 and 4 are the best; looking at the efficiency, topologies 1 and 4 are better; finally, to obtain a good bandwidth it is better to select topology #2.

In average, it seems that the classical boost topology offers a good compromise among these analyzed parameters. The other options can be used to improve a particular feature such as weight or efficiency.

Considering the data obtained in this analysis, topology #4 is a very good option. Low ripple boost with ripple cancellation allows a big reduction of size and weight of the inductors. Also power losses are among the smallest and bandwidth can be higher than other options. It is a nice alternative but it has other drawbacks such as a floating transistor, a higher number of components (less reliable) and a complex inductor with three windings.

The interleaved boost is the best option in terms of weight and bandwidth but the power losses in its inductors penalized the efficiency.

The two inductor boost topology is clearly penalized if a small input current ripple is required forcing to have large inductors and losing the advantage of a reduced output capacitor that, in this case, is imposed by the system.

Boost with switch near ground allows the cancellation of the RHP zero but not for this particular specification. On the other hand, it is penalized by the weight of its main inductor.

Conclusions

In this paper, five boost topologies have been analyzed from the point of view of power losses, weight and control loop bandwidth. All these topologies have been designed, modelled and simulated and/or built to test its performance.

	number of transistors	number of inductors	number of caps.	Weight (gr)	Power losses (W)	Resonance frequency (Hz)
Classical boost converter	1	2	2	207.8	15.8	900Hz
Interleaved boost	2	4	3	161.3	19.9	1.86kHz
Two inductor boost	1	2	2	336.1	16.4	830Hz
LRB ripple cancellation	1	3	4	161.6	14.4	1.24kHz
Boost switch near ground	1	2	2	287.1	16.9	794Hz

Table 7.- Comparison of the five analyzed boost topologies

The classical boost converter appears as a very good option. It offers a good trade-off between simplicity efficiency and losses. Its bandwidth is limited by the RHP zero. Therefore, it is selected in most of the cases.

The low ripple boost with ripple cancellation is another very good alternative. Looking at he figures, it is a better alternative to the classical topology but its power stage is more complex.

The rest of the topologies are good from particular points of view but none of them are better for this particular set of specifications.

In this paper, the bode plots of these not-very-usual boost topologies are shown. It can be checked that many of them show a complex transfer function that limits its bandwidth.

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